A2. 23—CRUSTAL DEFORMATIONS OF GRADUAL TYPE

By B. GUTENBERG

Professor of Geophysics, Balch Graduate School of Geological Sciences, California Institute of Technology, Pasadena, Calif., U.S.A.

Crustal deformations of gradual type may be observed in very different ways: horizontal shifting of large areas may be found by astronomical observations (change in latitude), or by comparing radio time signals from far distant points with the astronomically controlled time of the place under consideration (change in longitude); movements of blocks, one relative to the other, may be discovered by geological investigations; clear indications of vertical movements are often shown by changes in shore-lines (direct observations) or by continuous records of tide gauges; finally, relatively accurate data are provided in all cases by geodetic measurement, either triangulation, or precise levelling.

Data from any method mentioned above are very scanty, and even by combining the results of all of them together, there is no considerable region of the earth for which a map showing recent changes can be drawn. Very rough results are available only for north-western Europe, for some parts of North America and for Japan. In addition, there are a few data concerning movements of still larger areas as a whole.

The most extended movements of a gradual nature, which perhaps may occur, are movements of the continental part of the earth's crust as a whole over the sima. Astronomical observations have shown that the north pole has been moving toward Greenland with an average velocity of about 14 centimetres per year during the last 40 years. This could be caused by a movement of the axis of the earth or by a movement of large parts of the earth's crust in the opposite direction, if the axis of the earth does not move relative to the body of the earth. Besides these observations made at a few stations especially equipped for this purpose, changes in latitude determinations of about $-1''$ have been observed during the last half century at most astronomical observatories in Europe, and in Washington, according to Wegener. Furthermore, Darling[1] has found the following changes in latitude in the United States: Mount Tom, 1862-1930, $-1''.1$; Mount Pleasant, 1869-1930, $-1''.6$; Des Moines, 1869-1930, $+0''.2$. However, it is not yet evident to what extent, if at all, these changes have been a spurious consequence of variations in refractions of light due to small changes in conditions at the observatories (for example, temperature).

Movements of large blocks of the earth's crust against each other have been investigated, especially by A. Wegener, whose theory of continental drift is based on such movements. In the last edition of his book[2] he gives the data shown in table 1.

The first three findings seem to be within the limits of error; the last is larger by far than the error probable in the case of the method then used, but an error of such amount is not wholly impossible. The measurement is to be repeated in 1933. Observations of the distance

[1] Darling, F. W. U.S. Coast Geod. Survey, Spec. Pub. 173, Washington, 1931.

[2] Wegener, A. Die Entstehung der Kontinente und Ozeane, 4. Aufl., Braunschweig, p. 25, 1929.

TABLE 1.—Changes in distance.

	Increase From	Increase To	Increase Metres	Average per year
North-east Greenland—Europe (observation of moon)	1823	1870	420	9
" " " " " "	1870	1907	1190	32
Godthaab —Europe (first observation of moon, second wireless)	1873	1922	980	20
" " (both by observation of wireless time signals)	1922	1927	180	36

between Europe and America have not given any probable changes at all up to date. R. Livländer[3] found the following distances between Cambridge, Mass., U.S.A., and Greenwich: 4h 44m+

1866	1870	1872	1892	1913-4	1926
30.891	31.065	31.016	31.108	31.000	31.013s
± .090	.056	.040	.037	.016	.016

and from the radio time signals 1922-7 the following changes in distance ("−" means decrease):

Potsdam-Washington	Paris-Washington	Potsdam-Ottawa	Greenwich-Washington	Average centimetres
+0.0002±0.0042s	−0.015±0.0075s	−0.007±0.017s	−0.0005±0.0068s	−21±28

Littell and Hammond[4] in 1927 found the distance from Washington to Paris to be 5h 17m 36.665±0.0019 which compared with two sets of observations of 1913-4 36.652±0.003 gives an average change of +0.32±0.08 metres per year. The only result of these observations is that the change in distance, if any, is less than half a metre a year. More accurate results will be available soon. Observations of this kind in other regions have given no clear changes up to date, but in a few cases we have measurements which are to be repeated from time to time, providing us with results within a few years. The following data have been given by Livländer[5]:

Tananarive (Madagascar) longitude 1890—3h 10m 07s±6s
1922 13 ± ?
1925 12.4±0.1s

Nosi-Bé, Hellville (Madagascar)
Longitude 1911—3h 13m 08.4s±4.5s Latitude 1888—13° 24′ 23.4″
1926 05.93±0.03 1903 23.5″

Cape of Good Hope longitude 1908—1h 13m 54.76s Alger 1905—0h 12m 8.38s
1926 54.596 longit. 1926 8.527

Gradual movements of smaller regions have not been studied with the accuracy necessary for this purpose and, as mentioned above, only over a very small time interval in a few regions. The best-known movements of this type are the uplift of the Great Lakes region in North America[6] and of Scandinavia. Already in the early part of the 18th

[3]Livländer, R. Geophysik, vol. 6, p. 134, 1930.
[4]Littell, F. B. and Hammond, J. C. Astron. J., vol. 38, no. 908, p. 185, Aug., 1928.
[5]*Op. cit.*
[6]For details compare Gutenberg, B., Tilting due to glacial melting (in preparation).

century Celsius found that the shores of the Baltic Sea were rising by an average amount of one centimetre per year. Investigations of tide gauge records by Witting[7] showed that these movements continued up to date, and that the uplift decreases gradually from one centimetre per year in the northern part of the Baltic Sea to zero near its southern shores. These movements, according to hypotheses of Born[8] and others, very probably are due to forces tending to restore the isostatic equilibrium which has been disturbed since the melting of the large ice-caps which covered this region during the Ice age.

Similar movements occur in the Great Lakes region where the records of gauges show that the northern shore of Lake Superior and the eastern part of Lake Ontario are moving upward nearly one centimetre per year as compared with the south end of Lake Michigan. In this case, too, the uplift changes gradually from point to point. The amount of maximum tilt connected with these movements is about half a foot per 100 miles or ten centimetres per 100 kilometres per century in northerly or north-easterly directions.

The corresponding coasts of the oceans are affected by these movements. There is an uplift of a few millimetres a year at some parts of the Pacific coast of Canada, whereas the Atlantic coast of this country seems to be stable now. Geological investigations show that during recent periods there had been an uplift on this coast also.

Investigations of the tide gauge readings of the United States by Gutenberg[9] showed that subsidences of land seem to occur at its south-eastern coast with a maximum very probably not over half a centimetre per year. Along the Pacific coast, especially in California, gradual changes seem to be very much more irregular. A slight subsidence (about one and a half millimetres per year at San Diego, and still less to the north) seems to interfere with irregular block movement.

Very much larger movements of the west coast of France have been calculated by Schmidt[10] who compared levellings between 1857 and 1864 and between 1884 and 1893. If his results are right, the maximum subsidence of land there occurs in north-western France and amounts to four centimetres per year or nearly 15 feet in 100 years. On the other hand, these changes are so large that their direction at least seems to be true, and, in addition, they do not disagree with the data which have been found for other parts of central Europe and indicate that the amount of subsidence decreases gradually from west to east and that there is an uplift of about one centimetre per year in the Rhine region.[11] In Bavaria, moreover, Schmidt found horizontal move-

[7]Witting, R. Fennia, vol. 39, no. 5, Helsingfors, 1918; Geografisca Ann., p. 458, 1922.

[8]Born, A. Isostatie und Schweremessung, Berlin, 1923.

[9]*Op. cit.*

[10]Schmidt, M. Sitzungsberichte der Bayerischen Akademie der Wissenschaften, München, math.-phys. Klasse, p. 1, 1922.

[11]Gutenberg, B. Handbuch der Geophysik, vol. 3, p. 458, Berlin, Gebr. Borntraeger, 1930.

Wilser, J. L. Heutige Bewegungen der Erdkruste, erkennbar an Ingenieurbauten im Oberrhein-Gebiet, Stuttgart, 1929.

Schmidt, M. Sitzungsberichte, Akademie München, p. 373, 1918.

Schütte, H. Aus der Heimat, vol. 40, p. 325, 1927.

Weissner, J. Der Nachweis jüngster tektonischer Bodenbewegungen im Rheinland, Haarfelddruck, 1929.

ments from triangulation amounting to a maximum of about four metres (13 feet) in 100 years.

Besides the regions considered above there are many parts of the earth where geological evidence shows the existence of gradual changes in level. Such observations have been made near the coasts of the oceans, where strand lines, old moorings, relics of forests at the bottom of the sea, or changes in the depth of water in harbours indicate such changes. A well-known example of this type is the temple of Jupiter Serapis, a few miles north of Naples, Italy, whose pillars are closely pitted with holes of boring marine molluscs up to a height of nearly 20 feet, which indicates that this region has moved down and afterwards risen by about this amount.

By use of such indications and others it has been found that large parts of the coast of Siberia and land around the islands of Spitzbergen have been rising;[12] the same seems to be true in the case of large parts of the Pacific coast of South America (Valparaiso, 19 feet in 220 years?) and in Japan where, according to Milne, the eastern and southern shores are rising (maximum two and a half centimetres per year) and the western side is sinking (maximum six centimetres per year?).

Unfortunately correct geodetic measurements, either levelling or triangulation, were not started until recently, and in a few cases only has the geodetic work been repeated in such a way that changes could be found with the accuracy which is necessary. The oldest results are to be found in some parts of England. According to Milne[13] levelling in Lancashire and Yorkshire was carried out between 1843 and 1850, and afterwards between 1888 and 1894. "Excepting in the coal and salt districts, no material changes were found to have taken place." "Again in 1897 a line of levels was run from Blackgang to Freshwater in the Isle of Wight, through St. Catherine's Tower, which stands on a chalk hill 781 feet in height. The level of the beach mark on the Tower agreed exactly with that obtained in 1853."

The first repetition of levelling, made to find out whether changes occur during an earthquake, seems to have been carried out between Mainz and Darmstadt in Germany. In this region, around Gross-Gerau very many slight shocks ("Schwarmbeben") occurred from 1869-74[14] with a maximum intensity of seven on the Mercalli-Sieberg scale. Frank, who has collected the data on these shocks, suggested to the "Hessische Landesaufnahme" that they repeat their levelling of 1869. This was done in 1880, but no noticeable change was found. In 1913, again, the levelling was repeated, according to a letter of the "Hessisches Landesvermessungsamt". The difference in height of the mark at the station in Gross-Gerau between 1869 and 1913 has been calculated to be only a very small fraction of a centimetre (less than 0.1 inch), which means zero within the limits of error.

In other cases gradual changes within limited areas have been found, which are caused by "block movements". The only results affecting larger areas, France and Bavaria, have already been mentioned. In the region of the Niederrhein (Rhein around Dortmund-Wesel) re-levelling showed very poor agreement. Therefore, on the line Haltern-Wesel-

[12]Geikie, A. Text-book of Geology, p. 377, London, 1903.
Milne, J. Seismology, p. 2, London, 1908.

[13]*Op. cit.*

[14]Landsberg, H. Gerlands Beiträge zur Geophysik, vol. 34, p. 367, 1931.

Geldern-Dammerbrook levelling was carried out in 1921, 1922, 1925, 1927, and 1930.[15] Supposing that the height of Haltern remained unchanged, the height of the other end of the line was found to be the same within half a millimetre (0.02 inches) except in 1927, when the measured difference (perhaps caused by error) was two millimetres (0.08 inches). The length of the whole line is about 34 kilometres (20 miles). Noticeable changes, however, occurred between Schermbeck and Freudenberg. The maximum change was in the same direction, corresponding to a subsidence of the surface over all intervals by the following amounts in millimetres (one millimetre is about 0.04 inches):

1921 to 1922	1922 to 1925	1925 to 1927	1927 to 1930
1	2½	2½	3½

or a total of one centimetre (0.4 inches) in nine years.

Wilser[16] compared the results of two precise levellings along the south-western slope of the Schwarzwald against the Rhein valley. The maximum differences are about three centimetres (one inch) in 50 years in both directions, up and down. They agree with the results, found by the author previously[17] in completely different ways. The distance between the region of maximum uplift and maximum subsidence is about ten miles. These occur where the line of levelling passes from a lower (subsidence) to a higher terrace (uplift) and then back to lower terraces (subsidence).

In California block movements seem to occur to a very large extent, as has been mentioned above. Geodetic measurements have been carried out and have been repeated in a few cases, but the time elapsed since these investigations were started is not long enough to give decisive results. A comparison of triangulation, made before 1900 and repeated between 1922 and 1925, indicated movements, not exceeding seven feet (two metres), around the San Andreas fault[18] in northern California, which originated perhaps during the earthquake of San Francisco in 1906. Precise levellings seem to indicate well-marked changes in height, especially across some fault zones. Many reliable results are to be expected within a few years. The results of astronomical observations here, too, seem to indicate changes, but it is doubtful in this case also how far these results are influenced by errors.[19] Direct observations of such movements have been made recently[20] in Buena Vista oil field, where bent pipe lines and collapsed casings show that a block overriding another is moving southward at a minimum average rate of one and a half inches (four centimetres) per year.

Finally, much information on block movements has been given by levelling and triangulation in Japan.[21] There is hardly any volume of the

[15] Barsch, O. Gerlands Beiträge zur Geophysik, Ergänzungshefte für angewandte Geophysik, vol. 2, p. 14, 1931.

[16] Wilser, J. L. Zentr. Mineralogie, B., Jan., 1932.

[17] *Op. cit.*

[18] Bowie, W. U.S. Coast Geod. Survey, Spec. Pub. 151, Washington, 1928.

[19] Tucker, R. H. Bull. of the Seismological Soc. of Am., vol. 16, p. 170, 1926. Lambert, W. D. U.S. Coast and Geodetic Survey, Spec. Pub. 80, Washington, 1922.

[20] Koch, T. W. Analysis and Effects of Current Movements on an Active Thrust Fault in Buena Vista Oil Field, California. Paper presented at the meeting of the Pacific Section of the American Association of Petroleum Geologists, Los Angeles, Nov. 3, 1932.

[21] A list of levelling is given by: Muto, K., Japan J. Astron. Geophys., vol. 9, p. 99, 1932.

Bulletin of the Earthquake Research Institute, Tokyo Imperial University, which does not contain such data. Many investigations concern the neighbourhood of Sagami Bay, where the great earthquake of September 1, 1923, took place, especially Boso Peninsula, east of this bay, and Idu Peninsula to the west. Only a few of them may be mentioned here. According to the levelling between 1898 and 1924 (including the earthquake) the southern part of Boso Peninsula showed an uplift up to one and a half metres (5 feet), whereas in the same region there was a maximum subsidence of about ten centimetres (four inches) between 1924 and 1931.[22] Horizontal movements as calculated from triangulation at certain places amount to nearly one and a half metres (five feet). More data are available concerning Idu Peninsula. Levels were run in 1903 (I), 1923 (II), April, 1930 (III), November, 1930 (IV), and December, 1930 (V). Between I and II the great Kwanto earthquake (September 1, 1923) occurred; during 1930 earthquake swarms were felt, and between IV and V the Idu earthquake took place. The results of the levelling have been discussed by C. Tsuboi.[23] In his first paper he deals with changes along the northern part of the east coast of the peninsula, starting at a point about two kilometres north of Aziro and ending about 25 kilometres to the southward, south-east of the volcano Amagi. Supposing that the north end did not move, he finds the following changes:

	II-I centimetres	III-II centimetres	IV-III centimetres	V-IV centimetres	V-II centimetres
Near Aziro.........	+10	− 0	+ 1	+1	+ 1
Near Ito...........	+ 0	+ 5	+ 9	+2	+16
Near Kawana.......	− 2	+10	+12	+0	+22
North-east of Amagi	− 5	+ 2	+ 3	−0	+ 5
South end..........	− 2	− 3	− 2	−1	− 6

The second paper deals with results found from levelling around the whole peninsula. In its southern part the relative movements were small. If the peninsula moved, it sank practically as a whole. At the north end of the western coast there are signs of upheaval of a few centimetres. Tsuboi found by calculation that it is very probable that there was a general tilt of the peninsula down towards N. 50° W. between the intervals II-I and V-II by an amount of 2″ and 3.5″ respectively. The northern part of the peninsula, where it is connected with the main island, is crossed by faults, which were very active during the periods considered here. Along the Tanna fault, for example, the land to the east of the fault was displaced northwardly, relative to the land west of it, the amount of the dislocation, according to Tsuboi, being about 100 centimetres as measured on the surface of the ground. The maximum subsidence there, as found from levelling, was about 20 centimetres. Observations in a tunnel there showed gradual movements in addition to the earthquakes.[24]

Great changes in height occurred during the earthquake of 1923 on the land north of Sagami Bay between the two peninsulas considered above. The maximum upheaval occurred near the mouth of Sagami

[22] Miyabe, N. Part I, Bull. Earthquake Research Inst., Tokyo, vol. 9, p. 256, 1931; part II, *ibid.*, p. 407.

[23] Tsuboi, C. Bull. Earthquake Research Inst., vol. 9, p. 151, 1931; *ibid.*, p. 271; *ibid.*, vol. 10, p. 262, 1932.

[24] Takahasi, R. Bull. Earthquake Research Inst., vol. 9, p. 435, 1931.

River (one and a quarter metres) and in the southern part of Boso Peninsula (one and a half metres or five feet) according to N. Miyabe.[25] (Very much larger amounts have been reported from the bottom of Sagami Bay, but the writer favours the theory that they have been produced by slides of parts of the sea bottom, so far as they are true.) Subsidence of the bottom, up to nearly one metre (three feet), occurred north-west of the maximum depression, and another region of subsidence has been found near Tokyo, with a maximum of more than half a metre (about two feet) on the eastern side of the Sumidagawa River. A. Imamura[26] has attempted to show that the earthquakes in this region are only a sudden increase of these normal block movements. The levellings show that the maximum subsidence always takes place in the same region by an average amount of 1.4 centimetres (half an inch) per year. The following maximum changes have been found (in centimetres):

1892-95 — 1898 —	1902 —	1918 —	Nov. 1923 —	Jan. 1926 —	Feb. 1930
−2 −3	−3	−29	(−70*)	−18	(−56*)

*Means interval with strong earthquake.

Another earthquake region, where levellings have been repeated a few times, is the Tango district on the west coast of Japan, west of Tokyo. In a first paper, C. Tsuboi[27] discussed the movements during the period of a large earthquake, when the maximum amplitudes of vertical movements were about 80 centimetres in both directions and the horizontal displacements found from triangulation exceeded one metre. (They reached nearly four feet.) In a second paper he showed that during the three years after the earthquake all vertical movements which occurred were nearly proportional to those during the quake but with an amplitude of about one-tenth of these sudden changes.

Tilt seems to be the reason, according to Imamura,[28] for the changes in level which have been observed in the southern part of Sikoku, the island between Syukiu and Nippon. From 1895-1929 there took place a maximum subsidence of twenty and a half centimetres (eight inches) near Murotozaki in the south-east corner of the island and a maximum uplift of eleven and a half centimetres (four and a half inches) east of Koti. Furthermore, tilts connected with vertical changes of about a quarter of a metre (ten inches) were observed between 1899 and 1928 in the Kii[29] Peninsula, southern Nippon, east of Sikoku. The changes in level around Osaka, in the north-western part of this peninsula have been investigated by Umemoto.[30] There, too, the changes have occurred usually at the same places and in the same direction between successive levellings. The maximum subsidence has been found near Dozimahama-Dori: 1885-97—six centimetres, 1897-1900—two centimetres, 1900-7—five centimetres, and 1907-28—thirty-one centimetres.

Data concerning the Kyushiu Island (south-west Japan) and the

[25]Miyabe, N. Bull. Earthquake Research Inst., vol. 9, p. 1, 1931.
[26]Imamura, A. Japan. J. Astron. Geophys., vol. 8, p. 177, 1931.
[27]Tsuboi, C. Part I, Bull. Earthquake Research Inst., vol. 8, p. 153, 1930; Proc. Imp. Acad. (Tokyo), vol. 7, p. 234, 1931.
[28]Imamura, A. Japan. J. Astron. Geophys., vol. 8, p. 29, 1930.
[29]*Ibid.*, vol. 7, p. 31, 1929.
[30]Umemoto, T. Bull. Earthquake Research Inst., vol. 8, p. 86, 1930.

Mino Owari district (central Honshu) have been published by Tsuboi.[31] In the first case changes in height up to nearly one metre in about 20 years have been observed, which Tsuboi explains by assumption of tilting of about 10″. At the Mino-Owari fault, uplift of about three quarters of a metre has been found near one side and subsidence of about one-third of a metre at the other.

Direct observations of tilt have been started in Japan, too. Besides irregular tidal and seasonal movements a secular variation amounting to 17″ has been found[32] at Mount Tukuba.

---

[31]Tsuboi, C. Bull. Earthquake Research Inst., vol. 7, p. 103, 1929.

[32]Inouye, W. and Sugiyama, T. Bull. Earthquake Research Inst., vol. 8, p. 362, 1930, and vol. 10, p. 130, 1932.